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PROJECT OF WIND MOTOR WITH AERODYNAMIC TRANSMISSION FOR CAPACITIES OF 100 KW TO 3000 KW

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16. Abstract

To reduce excessive weight requirements in the design of a 100-3000 kw capacity wind motor, aerodynamic transmission is employed. Aerodynamic transmission involves mounting secondary small windmills at the ends of the main wheel blades of the wind motor. The secondary small windmills operate in a high-velocity relative stream of 40-70 m/sec and can produce energy directly from the wind with the windmills turning at 500 or more rpm, with an efficiency of 80 percent or higher.

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PROJECT OF WIND MOTOR WITH AERODYNAMIC TRANSMISSION FOR CAPACITIES OF 100 KW TO 3000 KW /65*

N. V. Krasovskiy

Presented by Academician S. A. Chaplygin

Besides increasing the diameter, for the same wind velocity the capacity of a wind motor of the same type increases in proportion to the square of the diameter, its rpm decreases in proportion to its diameter, while the torque rises in proportion to the cube of the diameter. One of the "bottlenecks" of large-diameter wind motors is the need to transmit large capacities from the wind motor wheel to the generator at low rpm's. As an example, let us show that the main reduction gear even for the TsVEI /Central Scientific Research Institute of Wind Power/ wind motor, D = 50 m, with a 1000 kw generator designed by the Orgametall /Trust for the Rationalization of Production in the Machinery and Metalworking Industries/, has a diameter of 3 m and a width of 750 m. For a wind motor with D = 80 m and a 15-18 rpm wheel together with a 4000 kw generator, the design of the gear drive poses major difficulties. Under the project of a 10,000 kw wind-electric station of the system of P. K. Gorchakov and Yu. V. Kondratyuk -- consisting of two wheels of D = 80 m wind motors mounted on the same reinforced concrete tower -- the total weight of the metal excluding the electrical section is 1660 tons. When mechanical or hydraulic reducers are delivered for the station, their weight will be 420 and 240 tons, respectively, that is 25.3 and 14 percent of the total weight of the metal used in the installation.

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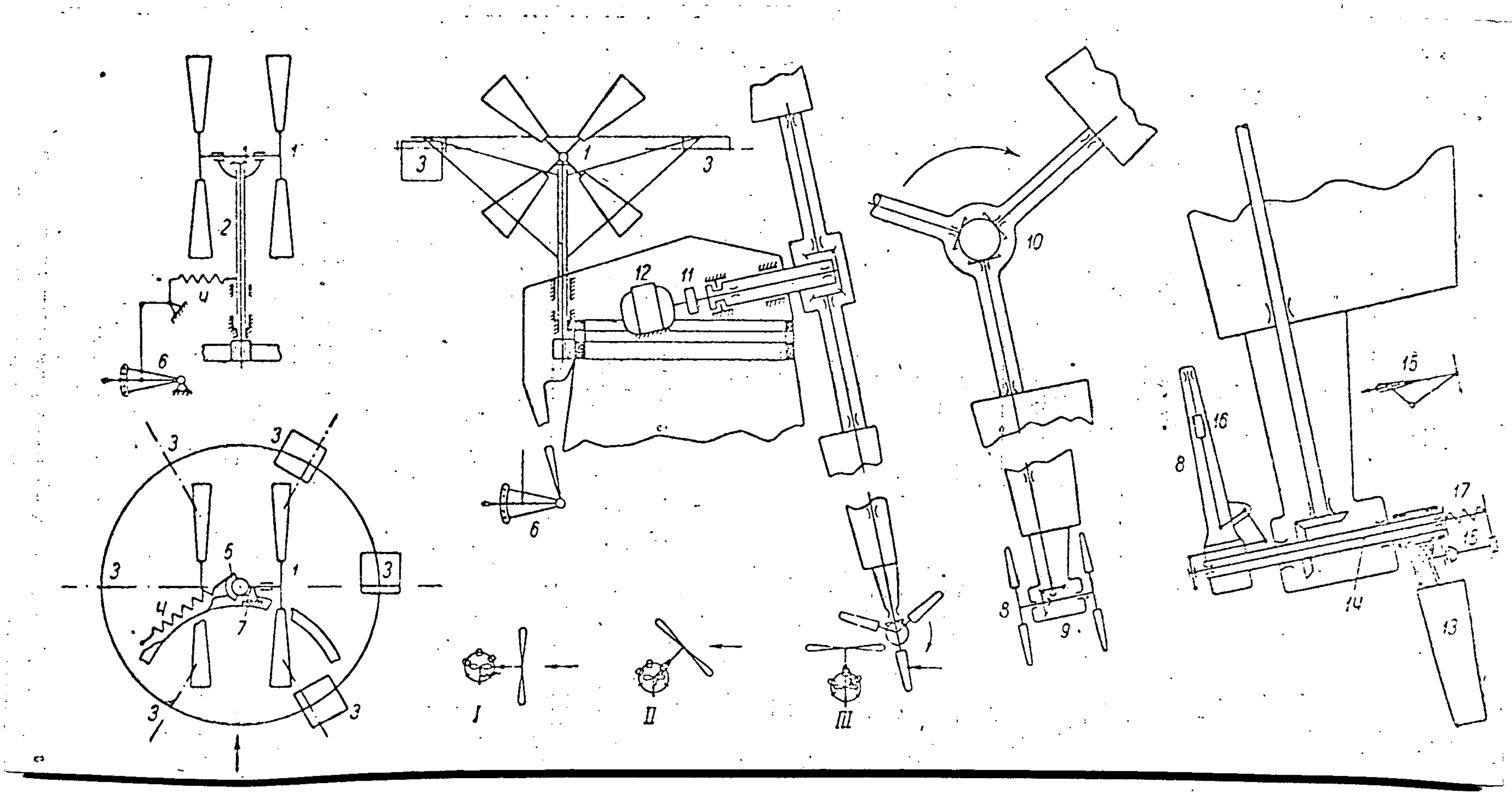

Fig. 1. Layout of N. V. Krasovskiy wind motor with aerodynamic transmission

Therefore, unquestioned interest is drawn to the aerodynamic transmission first proposed in the USSR in 1924 by A. G. Ufimtsev, which consists of placing secondary windmills at the ends of the main blades of the wind motor; the secondary windmills at the ends of the main blades of the wind motor; the secondary windmills operate in a relative stream of high velocities of the order 40-70 m/sec and make it possible to produce energy directly from the wind by means of these windmills at rpm values of 500 or more with efficiencies of 80 percent and higher. This energy from the secondary windmills is transmitted via thin shafts housed within the main blades of the wind motor to a high-speed generator installed in the head of the wind motor.

Also of interest is a second variant of the motor in which a special type of generator is located at the ends of the blades, and secondary small windmills are directly seated on the generator shafts.

Fig. 1 shows the layout of a wind motor with aerodynamic transmission we proposed based on the first variant. Secondary small windmills 8, via two gear drives 9 and 10, transmit rotation to generator 12. The generator is connected via a horizontal shaft of the gear drive to a Fettinger clutch 11 making it possible to operate in the network during brief gusts at moderate operating /67 wind velocities. The main blades of the wind motor are mounted immobily on flywheels. Rotation in the wind and partial departure of the plane of rotation of the blades of the main wheel of the wind motor from out of the wind at high wind velocities, regardless of direction, is provided with a windmill 1, which can rotate about its vertical axis 2. To the windmill mechanism is rigidly secured a system of six freely-suspended paddles arranged around the windmill mechanism on a special circular holder. These blades, when acted on by wind from one side of the circular holder, rotate about their axis and become aligned with the wind direction, not offering any resistance to the wind, while on the other side of the holder these paddles rest in special supports and receive the wind pressure with their entire area. The wind pressure on these paddles, regardless of the wind direction, is equalized by the tension in spring 4. One end of spring 4 is attached to the helix 5, while the other end -- via crank levers -- is attached to adjusting lever 6, with which the initial and final tension of spring 4 can be adjusted. Helix 5 rests in stop 7 when the windmill rotates by 90° during a storm; the stop rigidly fixes the extreme position of the windmill in a strong wind. The mutual arrangement of the plane of rotation of the main blades of the wind motor and the planes of rotation of the windmill in weak winds, strong winds, and storms is shown in diagrams 1, 2, and 3, respectively, in Fig. 1. The initial and final spring tension is set by manual regulation using lever mechanism 6.

The foregoing shows that operation in a network for all wind velocities is completely provided for by the self-regulating windmill and the Fettinger clutch. When there is a sudden disengagement of the load in the network or when the network operates in isolation with incomplete loading, maintenance of a constant rpm of the secondary small windmills is provided by the aerodynamic governor of the rotative velocity, located at the ends of the main blades of the wind motor. The governor consists of several blades 13 freely rotating about axis 14. Blades 13 are connected with each other with a kinematic coupling 15 and are kinematically connected via the lever mechanism and the shaft center with the centrifugal weights 16 placed within the blades of the secondary small windmills 8. The centrifugal weights 16 are equalized by tension in spring 17. The blades of the secondary small windmills 8 are rigidly secured on their flywheels. When the blades of the secondary small windmills reaches a specified rpm, the centrifugal weight 16 overcomes the resistance of spring 14 and brings the governor 13 blades, which up to this time had been oriented in the direction of the relative stream, into the working position. The drag of the freely rotating blade wheel encountered by the wind increases, and the blades of the secondary small windmills reduce their rpm.

Let us now turn to the aerodynamic calculation of the secondary windmills. Eq. (1) gives us, according to Professor Zhukovskiy /1_7, an expression for the wind energy use coefficient of an ideal (theoretical) wind motor wheel

$$\xi = \frac{T}{\frac{mv^2}{2}} = 2B\left(\frac{1}{2} \pm \sqrt{\frac{1}{4} - \frac{B}{2}}\right). \qquad (1)$$

Here T is the wind motor capacity, $mv^2/2$ is the kinetic energy of the air mass passing through the area swept by the wind motor blades per unit time at the velocity of the stream sufficiently /68
distant from the wind motor, $B = P/\left[(\rho \pi D^2/4)V^2\right]$ is the coefficient of drag loading per unit area swept by the wind motor of blades, and P is the ram pressure over the area swept by the wind motor blades.

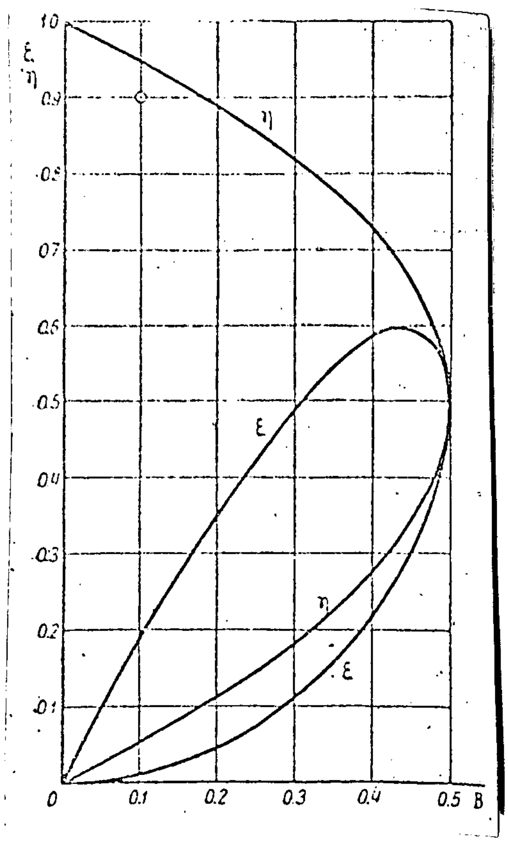

Fig. 2. Efficiency η and wind energy use coefficient ξ for an ideal wheel of a wind motor

Eq. (2) yields an expression for the wind motor efficiency, expressing the ratio of the capacity generated by the wind motor to the work required to overcome the drag on the wind motor wheel:

$$\eta = \frac{T}{Pv} = \frac{1}{2} \pm \sqrt{\frac{1}{4} - \frac{B}{2}}. \qquad (2)$$

In Fig. 2, the ram pressure coefficient B is plotted along the X axis, and the efficiency η and the wind energy use coefficient ξ are plotted along the Y axis for an ideal wheel of a wind motor.

According to the standard symbols of Professor N. Ye. Zhukovskiy in his vortex theory /2_7, for the wind motor wheel we have the following expressions for the derived symbols:

ram pressure

$$\overline{P}=\frac{B\overline{W}^2}{2}=\overline{I}\left[\left(1-\overline{r}_0^2\right)-2\lg\overline{r}_0\,\overline{I}+2\mu\left(1-\overline{r}_0\right)\overline{W}_1\right], \tag{3}$$

capacity

$$\overline{T}=\overline{I}\left[\overline{W}_1\left(1-\overline{r}_0^2\right)-\frac{2}{3}\mu\left(1-\overline{r}_0^3\right)-2\mu\overline{I}\left(1-\overline{r}_0\right)\right], \tag{4}$$

"surface condition"

$$\overline{W}_1(\overline{W}-\overline{W}_1)=\overline{I}(1+\overline{I}), \tag{5}$$

efficiency

$$\eta=\frac{T}{PW}=\frac{2\overline{T}}{B\overline{W}^3} \tag{6}$$

and wind energy use coefficient

$$\xi=\frac{4\overline{T}}{\overline{W}^3}.$$

Fig. 2 shows that we will have the optimal efficiency of a wind motor for minimum ram pressure coefficient B. Calculations showed that this requires that the blades have as large a lift-to-drag ratio as possible and the optimal value of: /69

$$\overline{W}=\frac{W}{\omega R},$$

where W is, for the given case, the velocity of the relative stream relating to the centers of rotation of the secondary small windmill wheels of the wind motor, which we will denote below as V, and ωR is the tip rpm of the secondary small windmill wheels, whose reciprocal is $1/\overline{v}$ = Z, a modulus that characterizes the speed of these small windmills. Calculations showed that the optimal value of C lies within the limits from Z = 1/0.3 = 3.33 to Z = 1/0.5 = 2. For the values of B = 0.1, Z = 2.0, and the lift-to-drag ratio of the blade given for its infinitely large span, μ = 0.01 that we adopted for our subsequent calculations, we got a secondary small windmill efficiency η = 0.895.

Fig. 3 and Table 1 present the lift-to-drag ratio, obtained by calculation, of our assumed secondary small windmill; Fig. 4 shows its design layout. In Fig. 3, the modulus is plotted along the X axis, and the wind energy use coefficient ζ and the ram pressure coefficient $B = P/\rho FV^2$ are plotted along the Y axis, where B is the ram pressure, $F = \pi D^2/4$ is the area swept by the wind motor blades, V is the velocity of the relative stream, and η = T/PV is the efficiency of the secondary small windmill, where T is the capacity of the small windmill. The number of blades was taken as three.

TABLE 1

Relative radius $\bar{r} = \frac{r}{R}$	Radius in m r	Relative wing thickness $\bar{b}$	Wing width in m b	Angle of wing ch chord w/ plane of rotation σ	Relative wing thickness δ/b	Wing thickness in m δ
0.875	0.875	0.0298	0.125	23° 58′	0.12	0.015
0.625	0.625	0.0347	0.145	32° 47′	0.15	0.022
0.375	0.375	0.0485	0.202	48° 45′	0.185	0.037

TABLE 2

Relative radius $\bar{r} = \frac{r}{R}$	Radius in m r	Relative wing thickness $\bar{b}$	Wing width in m b	Angle of wing chord w/ plane of rotation α	Relative wing thickness δ/b	Wing thickness in m δ
0.875	13.1	0.0232	1.460	4° 35′	0.12	0.175
0.625	9.375	0.03375	2.120	9° 55′	0.15	0.318
0.375	5.625	0.0465	2.920	19° 23′	0.2	0.584

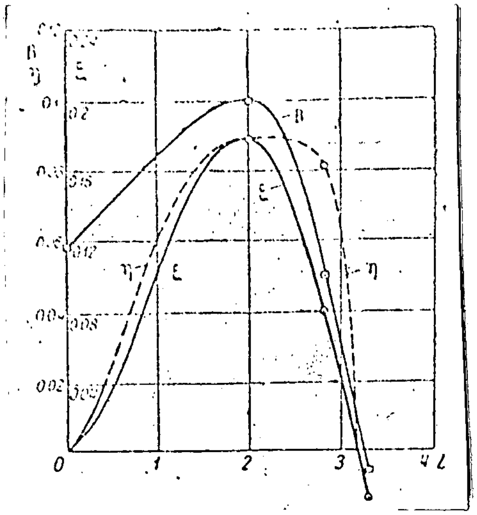

Fig. 3. Characteristic of secondary small windmill /70

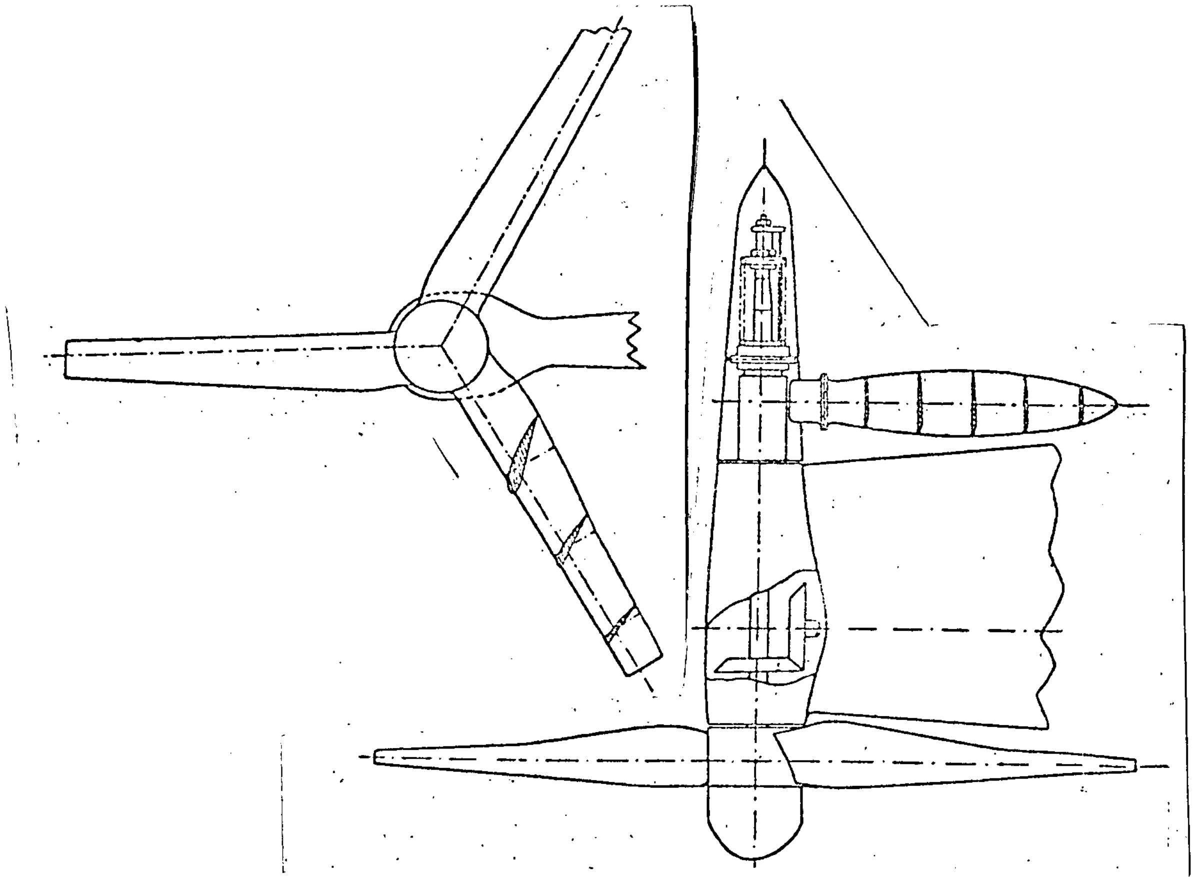

Fig. 4. Design layout of secondary small windmill and aerodynamic governor mechanism

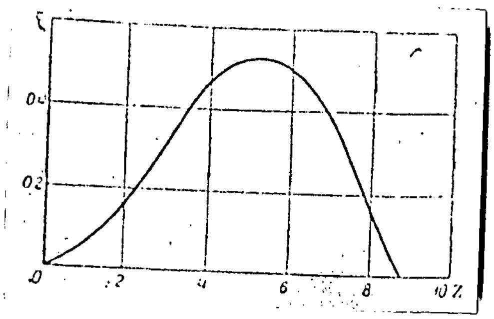

Fig. 5. Characteristic of main wheel of wind motor

Let us now calculate the wheel with aerodynamic transmission. /71

Fig. 5 and Table 2 show the calculated lift-to-drag ratio of the wind motor we assume for our further calculations. The wind profile was taken as the "Espero" according to the tests made by the TsAGI /Central Scientific Research Institute of Aero-hydrodynamic Institute7.

The relatively high wind energy use coefficient $\xi = 0.52$ we obtained is probably accounted for by the imprecision of applying in calculating wind motors based on the vortex theory the lift-to-drag ratio of wind profiles given for an infinite span. The probable value of ξ will be somewhat reduced within the limits down to 10 percent. Lacking experimental characteristics of wind motor wheels with modulus Z = 5, in our further calculation we relied on the characteristic (Fig. 5) that we got by calculations.

Fig. 6 shows the general appearance of our projected wind motor with D = 30 m and 150 kw capacity, with aerodynamic transmission as a model of a more powerful wind motor.

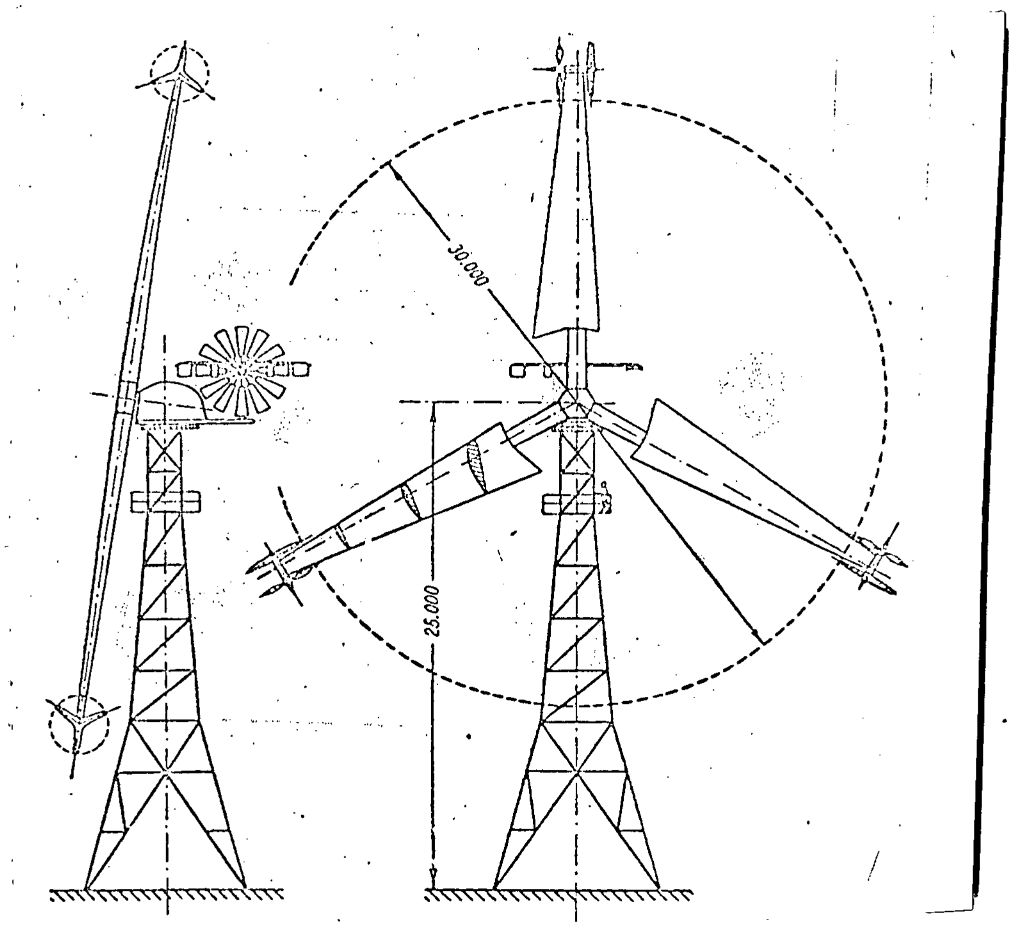

Fig. 6. Wind motor of the N. V. Krasovskiy system of aerodynamic transmission

In Fig. 7, the rpm of the mean wheel of the wind motor is plotted along the X axis. Along the Y axis is plotted the capacity (in kilowatts) generated by the main wheel of our wind motor for several wind velocities obtained after uninvolved calculations.

Plotted on the same graph are the capacities generated by the /72 secondary small windmills at different rpm values of the main wheel, given with respect to the capacity for this wheel. Here also are plotted the capacities generated by the small windmills given with respect to the generator terminals. These plots were also obtained by uncomplicated calculations.

The diameter of the secondary small windmills was selected so that their capacity with respect to the main wheel capacity intersects a family of curves in Fig. 7 expressing the capacity of the main wheel for different wind velocities as close as possible to the tops of the curves.

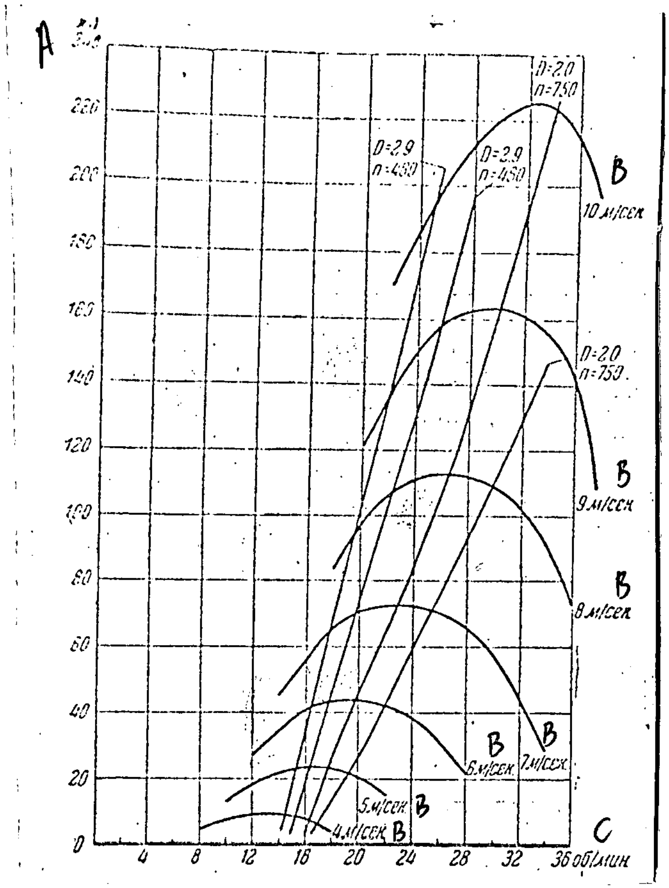

Fig. 7. Capacity of main wheel and secondary small windmills for different main wheel rpm's and different wind velocities

KEY: A -- kw
B -- m/sec
C -- rpm

Specifying the diameter of the secondary small windmills as 2.0, we obtain the calculated rpm of the main wheel of the wind motor, 34 rpm, and the rpm of the secondary windmills, 750 rpm. In this regime we however have extremely large centrifugal forces on the revolving blades of the aerodynamic governors. To reduce these forces, we limit the design rpm of the main wheel of the wind motor D = 30 to 25 rpm, tending to reduce the mean annual output, as will be shown below for an area with a mean wind velocity of 6 m/sec, from 395,000 kwh to 377,350 kwh, that is, by about 5 percent.

For large-diameter wind motors, we will be fully able to calculating installations for their optimal operating regimes, since both the centrifugal forces and the effect of gyroscopic moments in these cases is relatively decreased. For the case of a wind motor with D = 30 m, we obtained secondary small windmill diameters of D = 2.9 and their rpm n = 480. We oriented the planes of rotation of the secondary small windmills perpendicular to the plane of rotation of the main wheel of the wind motor.

The points of intersection of these two families of curves in Fig. 7 pertaining to secondary small windmills and the main wheel of the wind motor provide us with the capacities generated by our wind motor, with respect both to its main blades as well as to the generator leads. We transfer these data to Table 3, where the output of our wind motor for different operating regimes is calculated.

We obtain the mean annual optimal output of 377,350 kwh. From the data in Table 3 we can see that the maximum rpm of the main blades is 25.3 rpm. The main wheel of the wind motor for /73 various wind velocities from 5 to 10 m/sec operates at different rpm's, while preserving in a forced manner the same optimal operating regime for the highest wind energy use coefficient.

We see that the aerodynamic transmission allows the wind motor to use all operating wind velocities under the optimal conditions.

TABLE 3

Wind velocity in m m/sec	Frequency in hr	Power at generator term. in kw	Output in kwh	Rot. velocity of main wheel in m/sec	Modulus of main wheel	Wind energy use coefficient	Efficiency of aerodynamic transmission
0—4	3 720	—	—	—	—	—	—
5	940	9	8 450	14.8	4.64	0.52	0.77
6	827	24	19 900	16.5	4.32	0.5	0.88
7	687	45	30 900	18.0	4.02	0.48	0.89
8	570	69	39 300	19.8	3.88	0.46	0.89
9	462	101	46 600	22.2	3.87	0.46	0.89
10	365	147	53 700	25.3	3.97	0.47	0.87
11 & higher	1 189	150	178 500	—	—	—	—
			377 350				

We must note that the conclusion we drew from a sample calculation of a wind motor with aerodynamic transmission is provisional in the sense that it does not allow for the interaction of the secondary small windmills and the wind energy use coefficient of the main wheel of our wind motor.

Experience in aviation where the swirling flow behind a propeller has no marked effect on the performance of the aircraft wings shows that even when applied to wind motor, especially when the secondary windmills are placed beyond the periphery of the wheel of the main blades of the wind motor, the secondary small windmills do not have an appreciable adverse effect on the wind energy use coefficient of the main wheel of our wind motor. Conversely, in the event that blade lengths are lengthened beyond their normal size up to the centers or even up to the outer edges of the diameters of the secondary small windmills, we can calculate on obtaining an additional increase in the capacity of the main blades of the wind motor of 5-10 percent due to the performance of the elongated sections of the wings located beyond the secondary small windmills.

The aerodynamic governor consists of freely rotating air propellers mounted on the shafts of the secondary small windmills and operating in the autorotation regime according to the scheme in Fig. 1, where as the rpm's of the secondary small windmills are increased, the governor propeller blades -- under the effect of the centrifugal regulators -- tend to be aligned with the planes of rotation of the blades and increase its drag relative to the stream.

We adopted the blade type and its characteristic according to Fig. 28 and Fig. 31 of an article by A. M. Izakson, "Performance of An Air Propeller in the Autorotation Regime" (Trudy TsAGI, No 47, Moscow, 1930). Fig. 8 shows the general appearance of blade 13 of our adopted propeller, and Figs. 9 and 10 give the composite graphs of the loading coefficient on the area swept by the propeller

blades $C_x = Q_x/\rho SV^2$, where Q_x denotes the drag over the area swept /74
by the propeller blades S, ρ is the density of air, and V is the velocity of the relative stream. By Fig. 10, we assume $C_x = 0.74$ for our further calculation.

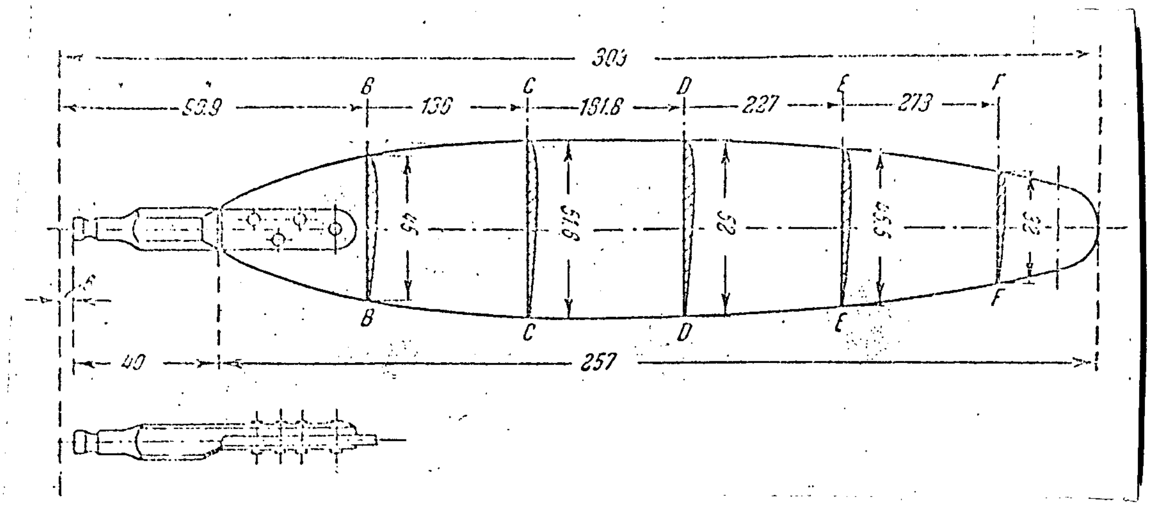

Figure 8

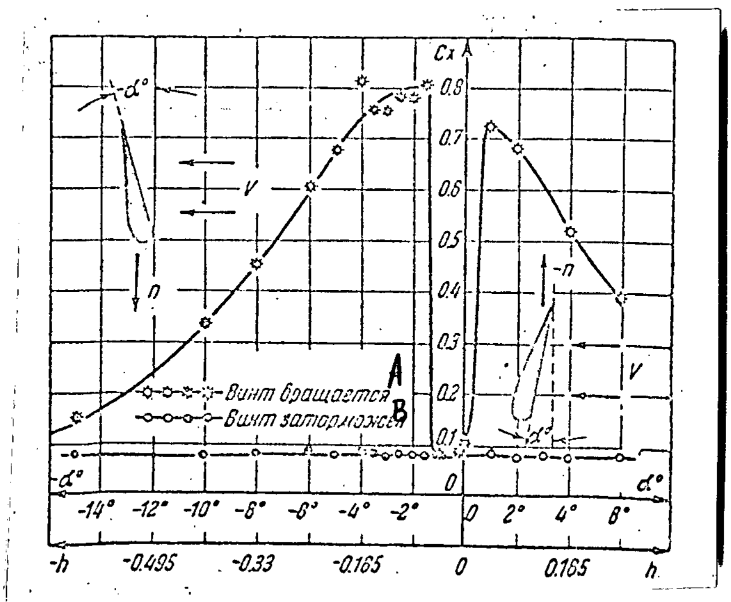

Fig. 9
KEY: A -- Propeller rotates
B -- Propeller is immobile

The total capacity of 150 kw or a wind motor with D = 30 m is achieved for a 10 m/sec wind velocity. With a further increase in wind velocity, the area of rotation of the wheel is automatically brought from beneath the wing by means of the self-regulating windmill. The diameter of the aerodynamic governor propellers are chosen so that the governor can maintain a constant rpm for the secondary small windmill blades of 480 rpm, in the event that the rotation of the main blades of the wind motor occurs without load with the onset of a gust of wind bearing double velocity (as against the mean wind velocity at 10 m/sec), that is, a wind velocity of 20 m/sec. Fig. 11 shows that the diameters of the aerodynamic governor propellers of 2.7 m are entirely sufficient for this purpose.

The synchronous modulus of our adopted secondary small windmill, according to Fig. 3, is Z = 3.15. The assumed rpm of the secondary small windmills is n = 180 rpm. Let us obtain the velocity of the relative stream required for the secondary small windmills to operate under these conditions: /75

$$W = \frac{\pi n R}{30 Z} = \frac{\pi \cdot 480 \cdot 1.45}{30 \cdot 3.15} = 23.2 \text{ m/sec},$$

which, in turn, corresponds to the rpm of the main blades of the windmill, $n = (30 \cdot 23.2)/16.5\pi = 13.5$ rpm. In Fig. 11, the rpm values of the main blades of the windmill with D = 30 m are plotted along the X axis, and along the Y axis -- the wind motor capacities given with respect to the blades of the secondary small windmills. The individual curves pertain to various wind velocities that are correspondingly shown in Fig. 11.

From Fig. 11 we see that at a 20 m/sec wind velocity and the 13.5 rpm main wheel velocity, the motor generates a capacity of 195 kw. The propellers of the aerodynamic governor at this rpm of the main blades and D = 2.7 m will absorb a capacity of $N = (3 \cdot C_x \cdot \rho S V^3)/102 = 195$ kw. At other rpm's of the main wheel of the wind motor, the propellers of the aerodynamic governor will absorb a capacity according to the curve shown in Fig. 11.

Thus, the governor we proposed is wholly capable of handling the task imposed on it. It is necessary to take up the question of the behavior of the governor during the time when the rpm of the

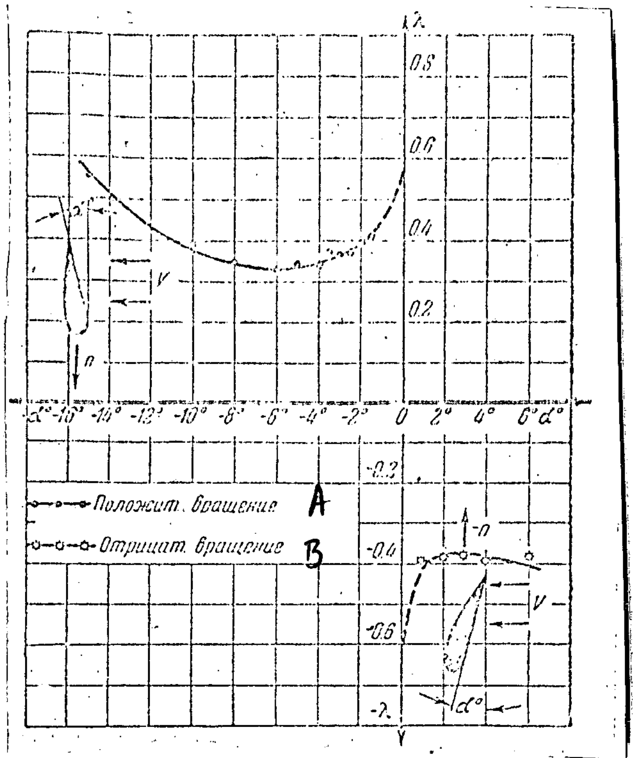

Fig. 10

KEY: A -- Positive rotation

B -- Negative rotation

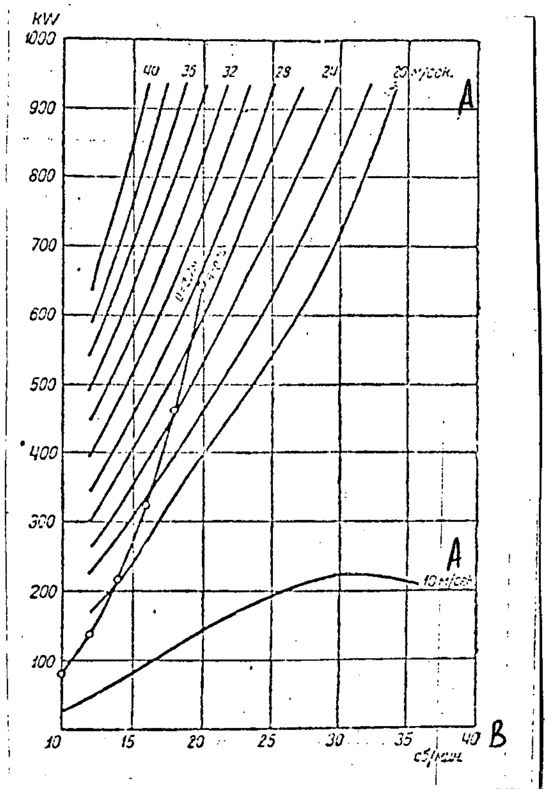

Fig. 11

KEY: A -- m/sec

B -- rpm

main blades of the wind motor pass from 25 to 13.5 rpm, during a sudden unloading and ensuing onset of a 20 m/sec wind gust. When the axes of rotation of the revolving blades of the aerodynamic governor of propeller are oriented so that the moments of the aerodynamic forces acting on these blades are close to zero, in the event of a sudden alignment of the revolving blades of the propeller with the plane of rotation of the propeller blades in the operating condition shown above, without loading, at a 25 rpm main blade speed, very great forces will begin to act on the governor blades, increasing by more than five times the ordinary forces, and the propeller can break. However, the suitable selection /76 of the orientation of axes of rotation of the aerodynamic governor propeller blades closer to the leading edge of the blades and allowance -- in calculating the centrifugal governor -- for the moment of the aerodynamic forces of the propeller blades relative to their axes of rotation -- can afford some gradualness in the rotation of the aerodynamic governor of propeller blades with reduction in the rpm of the main blades of the wind motor from 25 to 13.5 rpm.

Calculation of the governor with allowance for this factor will be subsequently assumed to be done in the future in the development of the technical project of a wind motor with D = 30 m with aerodynamic transmission.

A design diagram of the secondary small windmill snall windmill and the aerodynamic governor for a wind motor with D = 30 m is shown in Fig. 4. Strength calculations show that this mechanism is fully feasible.

Table 4 presents the composite operating characteristics of wind motors with aerodynamic transmissions for wheels of various diameters, from 8 to 80 m, corresponding to capacities from 5 to /77 4500 kw. The table shows the applicability of aerodynamic transmission for wind motors of all capacities within the limits shown in the table. From the data in Table 4 it is clear that the gyroscopic moments acting on the blades of the secondary small windmills do not produce major difficulties in designing wind motors with aerodynamic transmission. Some reduction in the installed capacity of the wind motor, without decreasing appreciably the mean-annual output of the motor, will additionally greatly facilitate the operating conditions of the aerodynamic transmission.

Summing up, we can note several properties of our proposed wind motor with aerodynamic transmission:

a) A wind motor with aerodynamic transmission makes it possible to directly produce from the wind capacities of 150-5000 kw at shaft rpm of 500 or more.

TABLE 4

Engine characteristics	Main wheel diameter, m				
	8	30		80	
Diameter of sec. windmill in m	0.9	2	2.9	5	7
Mean ann. wind velocity in m/sec	5	6	6	9.06	9.06
Capacity of generators inst. on wind motors, kw	5	150	150	4 500	4 500
Mean ann. output for generator terminals, in kwh	—	395 000	377 350	10 650 000	11 130 000
Wind velocity at which supply of energy into network begins, in m/sec	4	5	5	7	7
Rpm of main wheel for wind velocity shown in preceding item	40	17.8	15.3	10.5	8.3
Wind velocity corres. to total generator capacity, in m/sec	7.5	10	10	16	17
Rpm of main wheel for wind velocity shown in preceding item	75	34	25	20.7	16.7
Rpm of secondary windmills	1 000	750	480	550	300
Moment of gyroscopic forces acting on secondary windmill blade, in kg/m	—	43.5	133	1 896	4 520
Moment of ram pressure induced at blade of secondary windmill, in kg/m	—	31.8	52.3	1 570	2 700
Ratio of moment of gyro. forces to moment of ram pressure	—	1.37	2.54	1.21	1.62

b) The main blades of the wind motor operate at various wind velocities in the optimal regime, at constant modulus corresponding to the maximum wind energy use coefficient. Increasing the output by allowing for the efficiency of the aerodynamic transmission as compared with a wind motor operating at constant rpm is achieved in the limits 5-12 percent.

c) The rigid mounting of the power-producing blades ensures quiet engine operation and reduces the distance from the wheel

c) The rigid mounting of the power-producing blades ensures quiet engine operation and reduces the distance from the wheel center to the center of the tower, which means a reduction in the weight of the head.

d) The weight of the motor, compared with the weight of motors operating at constant rpm, is reduced by 10-20 percent by doing away with the cumbersome gear reducer and by increasing the generator speed.

e) The aerodynamic transmission makes it possible to design wind motors of large capacities compared with wind motors operating at constant blade rpm's.

The foregoing leads the conclusion that it is useful to perform the necessary calculation and experimental work in realizing our proposed type of wind motor with aerodynamic transmission.

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